Solar Hydrogen Production System Simulation Using PSCAD

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ABSTRACT

Hydrogen is a potential future energy storage medium to supplement a variety of renewable energy sources. It can be regarded as an environmentally-friendly fuel, especially when it is extracted from water using electricity obtained from solar panels or wind turbines. One of the challenges in producing hydrogen by using solar energy is to reduce the overall costs. It is therefore important that the system operates at maximum power. In this paper a PSCAD computer simulation based on a water-splitting, hydrogen-production system is presented. The hydrogen production system was powered by a photovoltaic (PV) array using a proton exchange membrane (PEM) electrolyser. Optimal matching between the PV system and the electrolyser is essential to maximise the transfer of electrical energy and the rate of hydrogen production. A DC/DC buck converter is used for power matching by shifting the PEM electrolyser I-V curve as closely as possible toward the maximum power the PV can deliver. The simulation shows that the hydrogen production of the PV-electrolyser system can be optimised by adjusting the converter duty cycle generated by PWM circuit.

Keywords – Renewable - photovoltaic- solar hydrogen- PEM electrolyser.

1 Introduction

In recent years, the central aim of world energy policy has been to develop renewable energy sources and share the energy they produce to reduce dependence on fossil fuels and to reduce the harmful emissions that result when they are burned. To fully take advantage of the environmental benefits of hydrogen, it must be produced from a renewable feedstock (renewable energy), but most of the hydrogen that is currently produced is derived from natural gas, which is a non-renewable fossil fuel.

Hydrogen produced from renewable energy sources offers the promise of a clean, sustainable energy carrier that can be produced from domestic energy resources around the globe. One method of hydrogen production using a renewable energy source is the electrolysis of water using renewable electricity, i.e., electricity generated from photovoltaic cells, wind turbines, hydroelectric turbines, or generators fuelled by biomass.

Several potential applications for electrolysis use solar- and wind-produced electricity. Solar PV cells and wind turbines convert solar energy and wind power, respectively, into electricity that can be used to produce hydrogen from water by electrolysis. Electrolysis using solar energy is a very attractive process to produce hydrogen .The exploitation of this important potential comes through the conversion of the solar energy to an energy vector that is versatile, storable, transportable and ecologically acceptable. Today, hydrogen seems to be the best candidate

2 Components of the solar hydrogen production system

Hydrogen production through water electrolysis using solar photovoltaic cells to provide the required electricity is highly feasible. Both water and solar energy are available in huge amounts, and hydrogen provides an ideal means for storing and transporting electricity from solar energy. The PV uses light to generate DC electrical energy. The PV cell consists of one or two layers of a semi-conducting material (p-n junctions), usually silicon. When light shines on the cell, an electric field is created across the layers, which causes electricity to flow. The greater the intensity of the light, the greater the more power the PV cell delivers. The electric current produced by the PV cell is passed through water in an electrolyser, and the water molecules separate into hydrogen and oxygen. The most common electrolyser uses a proton exchange membrane (PEM) as a catalyst in the electrolysis process. In comparison to electrolysers that use a liquid electrolyte that must be replenished frequently, the PEM electrolyser has the advantages of producing very pure hydrogen, and requiring much less maintenance. In addition, it has easily scalable cells, and it can operate at much higher current densities than other types of electrolysers (1-2 A/cm2), with conversion efficiencies ranging from 50-90%. As mentioned earlier, electrolysers are thought to be a potentially cost-effective way of producing hydrogen locally. Electrolysers are compact and can realistically be located at existing fuelling places. Also, they offer a way to produce hydrogen with electrical power generated from renewable sources. Currently, renewable sources, such as solar, wind, and hydropower, produce only electricity, but the electricity they generate can also be used to produce hydrogen fuel through the use of electrolysers.

Figure 1 shows a PV hydrogen production system, which usually consists of the following main components: a PV array to supply the DC power to the system and PEM electrolyser; and DC-DC converter that consists of a control unit for power matching between the PV material and the PEM electrolyser and for providing the delivery of maximum power by PV material to maximize the hydrogen production rate.

Studies have been conducted on connecting solar PVs directly to an electrolyser (shown by the dotted path), thereby avoiding the need for a DC-DC converter. However, in this case, PV modules are not optimized to supply the most power the PV modules can deliver.

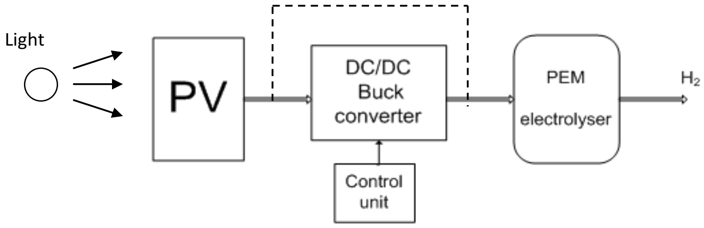


Figure 1: *Block diagram of a PV hydrogen production system*

One of the challenges in producing hydrogen by using solar energy (PV-Hydrogen system) is to reduce the cost. Therefore, it is important that the system operate at maximum power. This operation is usually achieved by matching the power generated by the PV cell with the power required to produce hydrogen.

3 PSCAD simulation

This part describes the use of PSCAD/EMTDC software to simulate the performance of a solar PV-PEM hydrogen production system.
System components:

Only the essential solar hydrogen production system components are included in this simulation programme. These components are the photovoltaic module, the DC-DC buck converter and the proton exchange membrane electrolyser.
The input data to the simulation programme are the solar irradiance hits the photovoltaic module, and the ambient temperature. The output results of the simulation are:

- Characteristics of the photovoltaic current, voltage, and power at standard test conditions (1000 W/m^2 and 25 °C).
- Current and voltage readings at the input and output of the DC-DC buck converter
- Characteristics of the electrolyser's current and voltage
- Characteristics matching of the photovoltaic source and the electrolyser
- The operating current of the system
- Hydrogen production rate

3.1 PV Model

The PV solar cell was modelled in PSCAD/EMTDC, as shown in Figure 2 There are two inputs and two outputs in this block. The inputs are terminal voltage and irradiance. The voltage varies from zero up to the open circuit voltage of the solar cell. The irradiance is assumed to be fixed at the standard test condition of 1000 W/m^2 .
The two outputs are the current and power delivered by the solar cell. The maximum current is controlled by the irradiance. (More irradiance gives more current.) The power is the result of multiplying the voltage and the current.

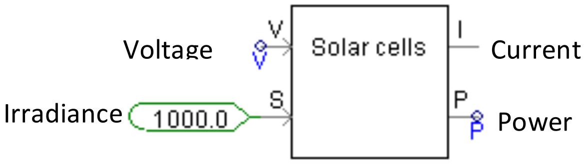


Figure 2: *Solar cell PSCAD block*

Table 1: *provides the parameters used in modelling a crystalline silicon solar cell [2] ,[7].*

Symbol/Value	Description	Unit
$q = 1.602\ \text{x}10^{-19}$	Electron charge	C
$k = 1.38\text{x}10^{-23}$	Boltzmann constant	J/°K
$n = 1.792$	Non-ideality factor	
$Ta = 293$	Ambient temperature	°K
$T_{ref} = 293$	Reference temperature	°K
$I\,sc = 2.0$	Short circuit current at reference state	A
$NOCT = 49$	Nominal Operating Cell Temperature	°C
$J\,o = 1.6 \times 10^{-3}$	Temperature coefficient	A/°K
$S = 1000$	Irradiance	W/m ^{2}
$I_{do}\,do = 71.1 \times 10^{-9}$	Diode reversal current	A

Table 1 Parameters used in modelling a solar cell based on a crystalline Silicon solar cell

The following equations were implemented in FORTRAN codes inside the block model:

$$T = T_a + S\frac{(NOCT - 20)}{800} \tag{1}$$

$$E_g = 1.16 - 7.02 \times 10^{-4} T^2 (T + 1108) \tag{2}$$

$$I_0 = I_{do}(\frac{T}{T_{ref}})^3 \exp(\frac{qE_g}{nK}(\frac{!}{T_{ref}} - \frac{1}{T})) \tag{3}$$

$$I_{ph} = I_{sc}\frac{s}{1000} + J_o(T - T_{ref}).. \tag{4}$$

$$I_d = I_0 \exp(\frac{qV}{nkt} - 1)... \tag{5}$$

$$I = I_{ph} - I_d \cdots \tag{6}$$

Where:

T = cell temperature.

T_a = ambient temperature.

I_0 = dark saturation current.

E_g = energy gap of cell semiconductor.

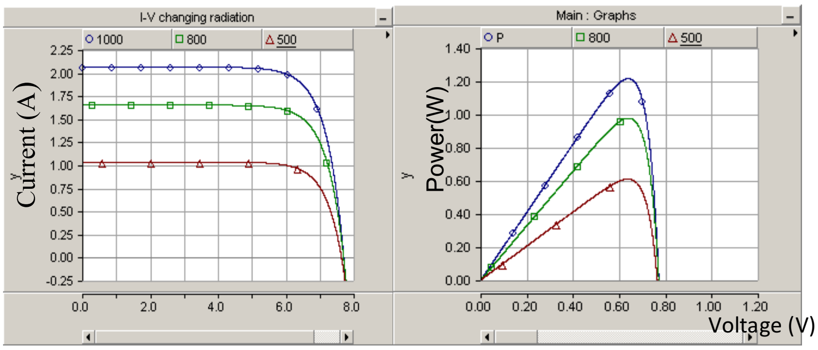
Id = diode current.

I_{ph} = photo current or light generated current.

V = cell output voltage.

3-1-1 Response of the solar cell to changes in irradiance

The characteristics of the solar cell at different levels of irradiance are shown below in Figure 3. The irradiance has a large effect on short-circuit current (the horizontal part of the I–V curves), while the effect on open-circuit voltage (the vertical part of the curve) is rather weak.



(a) *I-V characteristics* **(b)** *V-P characteristics*

Figure 3: *the effect of irradiance on current and power in the solar cell*

According to the voltage and power curves, the maximum output power of a photovoltaic cell changes with irradiance. When the irradiance is greater, the cell generates more power.

3-1-2 Response of the model PV solar cell to changes in temperature

As seen in Figure 4 as the cell temperature increases, the open circuit voltage decreases, whereas the short circuit current increases slightly. Increasing the temperature causes the voltage to decrease. This is a particularly severe problem, since the cell is often operated at the maximum power point, which is within the region.

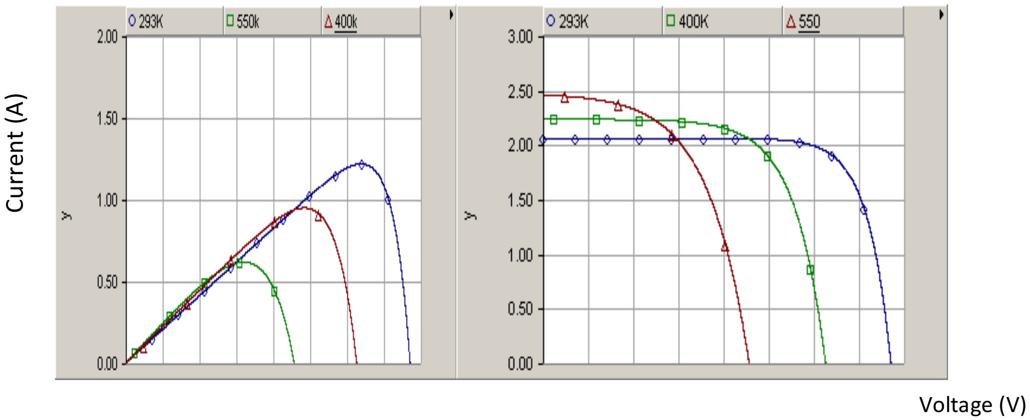


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Figure 4: *the effect of temperature on current and voltage*

The cell temperature varies because of changes in the ambient temperatures and because of changes in the levels of irradiance. Since only a small fraction of the irradiance on a cell is converted to electricity, most of that incident energy is absorbed and converted into heat.

From the simulation curve for the solar cell's I-V characteristics, we can see that the two values used to characterise the output of solar cells for a given irradiance level and operating temperature are:

1. Short circuit current, Isc, is the maximum current when the voltage is zero, i.e., the terminal points of the photovoltaic module are short circuited. The short circuit current is directly proportional to the available sunlight.
2. Open circuit voltage, Voc, is the maximum voltage when the current is zero, i.e., terminal points of the photovoltaic module are open circuited. The open circuit voltage increases logarithmically with increasing sunlight.

These two parameters are usually provided in the data sheets of PV modules. These parameters establish the operating point of the PV module along the I-V curve, i.e., the operating point moves along the I-V curve. It is desirable for the operating point to be at the point where maximum power from the PV module is generated. This is known as the maximum power point (MPP; $P_{mp} = V_{mp} \times I_{mp}$). V_{mp} and I_{mp} are the operating voltage and operating current at the maximum power point.

In practical applications, solar cells do not operate under standard conditions, because they are affected irradiance and temperature. Often, manufacturers provide plots that show the I-V curves shifting with irradiance and cell temperature changes.

3-2 Model of the PEM electrolyser

PEM water electrolysis is one of the most popular ways of producing pure hydrogen with compact equipment at a comparatively high level of efficiency. PEM is composed of a membrane, cathode, and anode, which produce hydrogen by providing pure water to one side of the polymer ion exchange film, which is placed between the anode and cathode.

The PEM cell is capable of high efficiency electrolysis under high current density conditions. The power consumption is proportional to the instantaneous current density, so the main consideration is the amount of current that can flow to the PEM cell from the DC-DC converter.

A unit PEM cell for water electrolysis was modelled by PSCAD/EMTDC block, as shown in Figure 5 the specifications for the cell are as follows:

- the operating temperature is 294 °K
- the effective area is 50 cm^2
- the maximum electrolyte current is 50 A
- the electrolyte voltage is 2 V

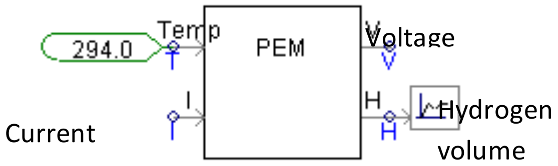

Figure 5: *PSCAD PEM electrolyser block*

The PEM model has two inputs and two outputs. The two inputs are current and temperature and the two outputs are voltage and the volume of hydrogen. The equations below govern the relationships between input and output variables.

The V-I relationship of a PEM cell is given by the following equations from [3],[4].

$$V = V_0 + \eta_c + \eta_a + IR, \qquad (7)$$

where V is PEM cell voltage, V_0 is the theoretical dissociation voltage, which depends on absolute temperature T (°K), as shown:

$$V_0 = 1.5 - 1.5e^{-3}T + 9.5e^{-5}T\ln(T) + 9.8e^{-8}T^2 \qquad (8)$$

The term η^{0} is an excess voltage on the cathode side, and its value varies from 0.05 to 1 V.

The term η^{a} is an excess voltage on the anode side, with a maximum value of 0.3 V.

R is the electrical resistance of PEM. In the simulation, the value of R is set to 0.037 ohm. The current (I) represents the current that flows through the PEM electrolyser.

Figure 6 shows the V-P characteristics of the PEM cell electrolyser model. The voltage-current graph shows that, for the PEM (Proton Exchange Membrane) electrolyser, the current only starts to flow at a certain voltage, after which it rises continuously. The slope of the curve is dependent on its equivalent ohmic resistance.

The applied voltage must be at least as large as the theoretical cell voltage in order for current to flow, which leads to a release of hydrogen at the cathode and oxygen at the anode.

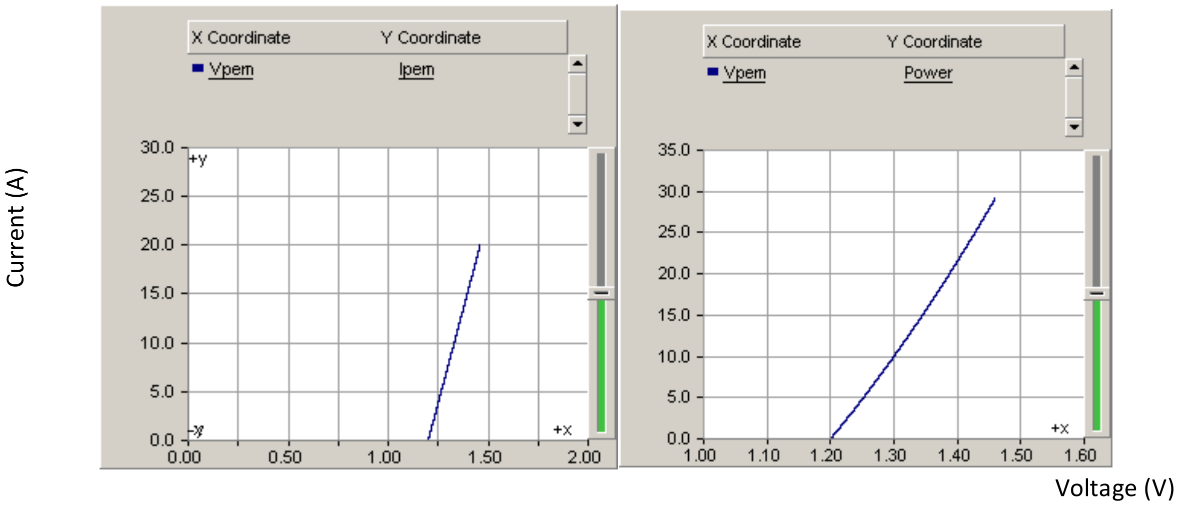

Figure 6: *I-V and V-P Curves for the PEM electrolyser PSCAD model*

4 PV–PEM electrolyser power matching using a DC-DC buck converter

The need for optimal power matching in the PV–PEM hydrogen production system is essential for maximum power transfer between the PV generator and the PEM electrolyser. The DC-DC buck converter is used for matching the power characteristics of both components.

Figure 7 shows the PSCAD/EMTDC simulation for the PV-PEM hydrogen production system using a DC-DC buck converter. The PV generator generates the DC power at standard conditions (1000 W/m^2 and 25 ^{0}C).

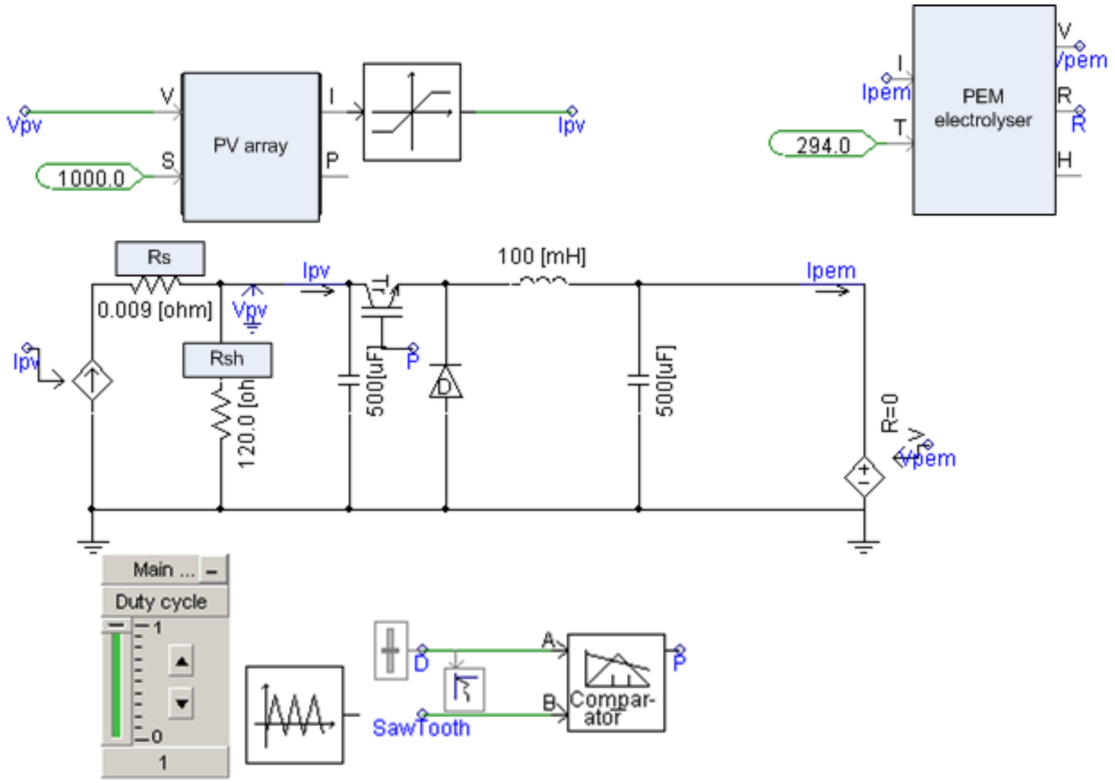

Figure 7: *PSCAD simulation of the PV-PEM electrolyser hydrogen production system using a buck converter*

The series resistance Rs and shunt resistance Rsh are calculated as follows:

$$Rs\langle\frac{0.01V_{oc}}{I_{sc}} \text{ and } Rsh\rangle\frac{100V_{oc}}{I_{sc}}$$

To generate different duty cycle values, a fixed-amplitude, saw tooth signal is compared with a changeable voltage level. A comparator produces pulses with different duty cycles. The pulses switch the buck converter switch on and off , and the durations of the on and off states control the relationships between the PV voltage Vpv and current Ipv and the PEM electrolyser voltage Vpem and current Ipem, as follows:

$$D = \frac{Ton}{Ton + Toff} = \frac{Vpem}{Vpv} = \frac{Ipv}{Ipem} \tag{9}$$

From equation (9), it is apparent that there is a different operating point for every duty cycle of the switch of the DC-DC converter.

The following PSCAD simulation results were obtained under standard irradiance (1000 W/m^2) and standard temperature (25 ^{0}C), and the measured values are volts for voltage readings and amperes for current values.

The power supply of the circuit is a PV module, and its characteristics are shown in Figure 8. The short-circuit current is 0.7 A, and the open-circuit voltage is 20 V; the operating voltage of the two-cell PEM electrolyser is approximately 5.8 V.

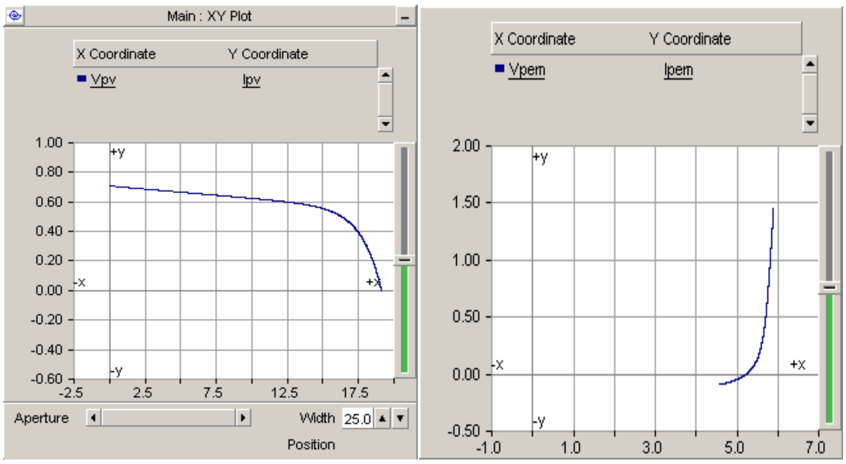

Figure 8: *I-V characteristics of (a) PSCAD model of the PV module and (b) PSCAD model of the PEM electrolyser*

Voltage, current, and power readings were taken at the terminals of the buck converter by varying the duty cycle value from 0.05 to 1 with scale of 0.5. As shown in Figure 9 , the operating voltage of the PEM electrolyser is considered to have an exponential shape with a maximum value of 5.8 V. The graphs show the power matching between the PV generator and the PEM electrolyser,

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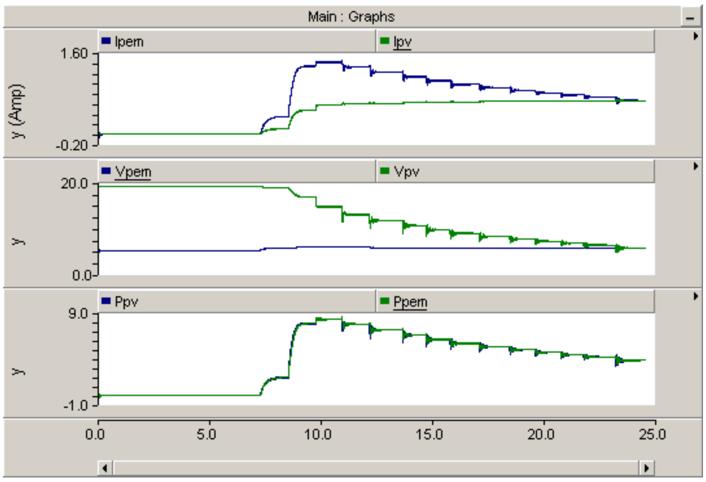

Figure 9: *PSCAD simulation results for the PV-PEM electrolyser*

where:

Ipem and Ipv are the PEM electrolyser and PV current values in (A), respectively

Vpem and Vpv are PEM electrolyser and PV voltage values in (V), respectively

Ppem and Ppv are yjhe PEM electrolyser and PV power in (W), respectively

From the previous results, it is apparent that the duty cycle governs the voltage and current on both sides of the buck converter, keeping the output voltage fixed at the PEM operating voltage. Current measurements at the power matching duty cycle (D = 4) show that the electrolyser current will be increased by about 2.5 times the PV operating current. This will increase the hydrogen production rate of the system while minimizing the solar PV area and decreasing the hydrogen production cost.
The power matching duty cycle D can be calculated, by using voltage and current values as follows:

$$dutycycleD = \frac{Vpem(V)}{Vpv(V)} = \frac{5.88}{14.71} = \frac{Ipv(A)}{Ipem(A)} = \frac{0.56}{1.40} = 0.4$$

The duty cycle needed to achieve maximum power point operation is equal to the ratio between the voltage of the PEM electrolyser and the PV array voltage at its maximum power point.

$$Dutycycle = \frac{V_{PEM}}{V_{mpp}}. \qquad (10)$$

The observation that the PV maximum power point voltage (Vmpp) has an almost linear relationship with the open-circuit voltage (Voc) of the solar photovoltaic module is apparent in the equation:

$$V_{mpp} = KV_{oc}.. \qquad (11)$$

Where K is a constant that has different values for different solar panels, and V_{oc} is the open-circuit voltage. The open-circuit voltage (Voc) can be measured by disconnecting the PV at regular intervals.
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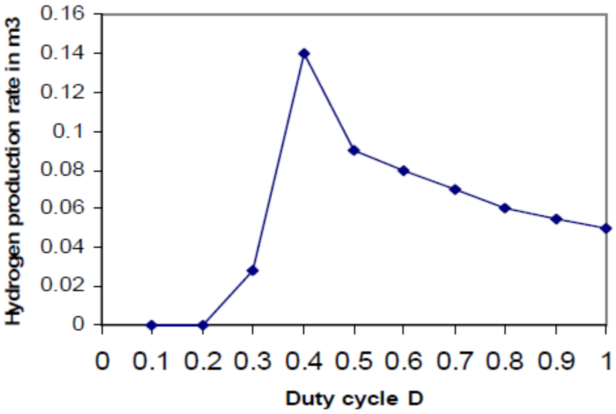

Figure 10: *Hydrogen production rate at different converter duty cycle*

The simulation shows that the hydrogen production of the PV-electrolyser system can be optimised by adjusting the converter duty cycle generated by PWM circuit. The strategy used was to fix the duty cycle at the ratio of the PV maximum power voltage to the electrolyser operating voltage.

5 Conclusion

A PSCAD software computer model was developed that was capable of exploring modelling for a photovoltaic-hydrogen production system with power matching using a DC/DC Buck converter. The evaluation took into account the different factors that affect the I-V characteristics of a PV array. The simulation proved that the operating voltage of the electrolyser and the PV voltage at maximum power were the key elements in power matching. The results show that the hydrogen production of the PV-electrolyser system can be optimised by adjusting the switch converter duty cycle generated by PWM circuit, the strategy used was to fix the duty cycle at the ratio of the PV maximum power voltage to the electrolyser operating voltage.

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